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Crystal shape effect on nuclear orientation thermometry at ultra-low temperatures

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Abstract. Absolute temperature measurement ($T < 100$ mK region) from anisotropy of gamma radiations emitted from oriented ^{60}Co nuclei in a single crystal of hcp cobalt is found to depend on the shape of the crystal. This dependence is attributed to some closure magnetic domains not oriented along the *c*-axis of the disc shaped crystal studied. A long rectangular strip of cobalt crystal is found to give correct angular distribution of γ-radiations and, therefore, suitable for thermometry.

Keywords. Ultra-low temperatures; nuclear orientation thermometry; closure domains.

1. Introduction

The angular distribution of gamma radiations emitted by oriented ^{60}Co nuclei has been given by Cox and Tolhoek (1953) as

$$W(\theta, T) = 1 - 15/7\, N_2 f_2 P_2 (\cos\theta) - 5 N_4 f_4 P_4 (\cos\theta) \tag{1}$$

where N_2 and N_4 are functions of spins of nuclear levels involved, $P_{2,4}(\cos\theta)$ are Legendre polynomials and f_2 and f_4 are orientation parameters calculated in terms of β defined as

$$\beta = \frac{\mu H_{eff}}{IkT} \tag{2}$$

where μ is the magnetic moment of ^{60}Co nuclei given by Lindgren (1964), I is its spin, k is Boltzmann constant, T is the absolute temperature and H_{eff} is the effective hyperfine field acting at ^{60}Co nuclei in ferromagnetic host of cobalt metal and known from NMR measurements of Portis and Lindquist (1965). Since all the parameters are known accurately the absolute temperature can be calculated from the gamma-ray angular distribution. This technique has been used to establish absolute temperature scales of two paramagnetic salts by Chandra *et al* (1967).

A single crystal of cobalt is particularly suited for thermometry as no external magnetic field is required for orienting the magnetic domains which are spontaneously aligned along the *c*-axis due to high uniaxial magneto-crystalline anisotropy (Bozorth 1947), and nuclei are aligned along the *c*-axis upon cooling the crystal to sufficiently low temperature ($T < 80$ mK).

2. Experimental results and discussion

Two single crystals of hcp cobalt* were employed for the measurements. One was taken in the form of a disc 3 mm in diameter and 0·2 mm in thickness with the c-axis in the plane of the crystal and the other a rectangular strip of dimensions $5 \times 1 \times 0 \cdot 3$ mm with the c-axis oriented along the length of the strip. The crystals were irradiated with thermal neutrons in Apsara reactor to obtain 20 μC of ^{60}Co and then annealed in high vacuum for three weeks at 380° C. In the adiabatic demagnetisation cryostat the thermal contact between the cooling paramagnetic salt and the cobalt crystal was achieved by soldering the crystal to one end of a bunch of copper wires which were compressed in the salt with a contact area of about 150 cm^2. Two scintillation detectors with Nuclear Data 512-channel analyser recorded the gamma-ray spectra in longitudinal and transverse directions with respect to the c-axis. The counting rates at low temperatures were normalised with respect to those at 1 K corresponding to isotropic distribution. The plane of detection of gamma radiations coincided with the plane of the crystal.

Figure 1 shows a plot of normalised longitudinal against transverse gamma-ray intensities. This method of plotting is not sensitive to small errors in positioning the detectors but is sensitive to any deviation from the theoretical angular distribution pattern of gamma-rays. The figure clearly shows an appreciable deviation of the observed pattern (triangular points) for a disc shaped crystal from the theoretical line, whereas the pattern for the rectangular crystal (full circles) shows no deviation.

These observations can be explained by assuming the presence of some ^{60}Co nuclei which are oriented in a direction different from the c-axis. This is possible as some closure magnetic domains are likely to be oriented in directions different from easy axis of magnetisation as explained by Craik and Tebble (1965). The closure domains are magnetised perpendicular to the c-axis and may be parallel or perpendicular to the crystal plane. The slope of plot of the observed data will

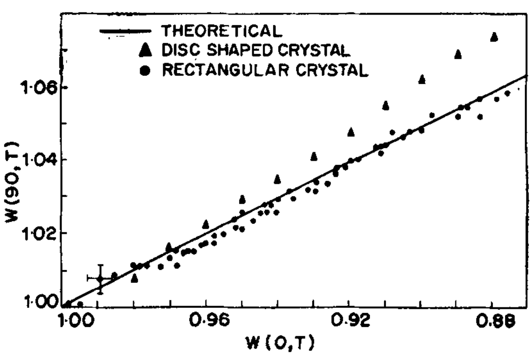

Figure 1. Plot of normalised transverse against longitudinal gamma-ray intensities for two cobalt crystals compared with the theoretical line assuming no closure domains. The range of temperatures covered is 15–80 mK.

* The cobalt crystals were obtained from Metals Research Ltd., Ergland.

be either greater or smaller than that of the theoretical line (which assumes no closure domains) depending upon whether the closure domains are magnetised perpendicular or parallel to the crystal plane. The observed slope is greater than the theoretical one indicating that closure domains in the disc shaped crystal are oriented perpendicular to the crystal plane. Hence these domains will affect only the gamma-ray intensities measured along the *c*-axis.

The observed gamma-ray intensity in such a case can be written as

$$W_{obs}(0, T) = (1 - a)\, W_c(0, T) + aW_c(90, T) \tag{3}$$

and

$$W_{obs}(90, T) = W_c(90, T) \tag{4}$$

where, $W_{obs}(\theta, T)$ and $W_c(\theta, T)$ are the observed and calculated gamma-ray intensities for $\theta = 0$ and 90° with respect to the *c*-axis and a is the fraction of ^{60}Co nuclei in the closure domains. Using these equations, the best fit with the experimental data for a disc shaped crystal is obtained for $a = 0{\cdot}18$.

These findings are significant in view of the fact that nuclear orientation thermometry is being widely used for precision low temperature measurements and choice of shape of the single crystal is important.

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